

Microstructure and mechanical properties of Al-12Si produced by selective laser melting

A S Fefelov¹, A G Merkushev¹ and O A Chikova^{1,2}

¹ FSAEI of HE «Ural Federal University named after the first President of Russia B.N. Yeltsin», 620002, 19 Mira St., Yekaterinburg, Russia

² Author to whom any correspondence should be addressed. E-mail: <chik63@mail.ru>

Abstract. Al-12Si specimens are produced by selective laser melting (SLM) from gas atomized powders. Installation for the production of powder is original. All specimens were prepared using the EOSINT M 280 device. A fine cellular structure is observed with residual free Si along the cellular boundaries. Room temperature tensile tests reveal remarkable mechanical behavior: the samples show yield and tensile strengths of about 102 MPa and 425 MPa, respectively, along with fracture strain of 12%. The study of crack surface morphology was shown by the example of a sample. Except the spherical pores, the interface of the molten pool also appears on the fracture surface, which indicates a mixture of fragile and ductile fracture. Additionally, the agglomerated silicon group appears also on the fracture surface.

Introduction

Selective laser melting (SLM) is an important additive manufacturing process for metal materials, which can produce parts with sophisticated shapes with small material wastage during production [1]. The part is firstly designed via the 3D computer-aided design (CAD) software, then built layer-by-layer with a high-energy intensity computer-controlled laser beam [2]. Until now, Al-Si alloys have been widely investigated and produced by the SLM process [3-7]. Due to their high wear resistance, the low thermal expansion coefficient and high strength to weight ratio, Al-Si alloys are used as structural material for engine blocks and pistons [8]. Owing to low thermal expansion and uniform distribution of its surface oxide film, eutectic Al-Si alloys are suitable for production using SLM. [9]. The microstructure and mechanical properties of SLM processed Al-12Si alloy had been studied before [3,6]. Compared with the conventional casted Al-12Si alloy, an additional and important advantage of the SLM processed sample is the ultrafine microstructure, which leads to improvement of the mechanical properties. Before this work, the feedstock materials of the SLM process for Al-12Si alloy were powders of brand EOS [1-3]. This powder presents good performance due to homogenous distribution of elements, leading to formation of uniform physical and chemical properties. In these studies of feedstock materials of the SLM process, powders of the Russian brand "AKD12" were used for the Al-12Si alloy. The installation for the production of powders is original, wherein all specimens were prepared using the EOSINT M 280 device. Therefore, it is interesting to compare the microstructure and mechanical properties of SLM processed Al-12Si alloy from epy Russia brand "AKD12" powder and brand "EOS" powders. Investigation of microstructure and mechanical properties was performed for SLM processed Al-12Si alloy.

Experimental Method



Powder Al-12Si of the Russian brand “AKD12” is manufactured on the original installation “UR-9” of gas spraying of metal melts. The UR-9 installation was developed at the Ural Federal University. This plant allows one to obtain metallic powders with median diameter $d_{50} = 25 \mu\text{m}$ (the diameter of 50% of powder particles does not exceed $25\mu\text{m}$). SLM-specimens were prepared using the EOSINT M 280 device. Investigation of microstructure and mechanical properties was performed for SLM processed Al-12Si alloy.

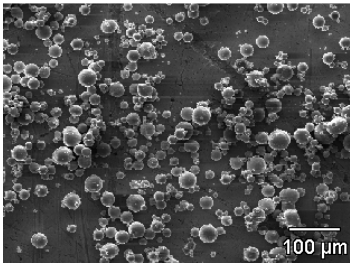
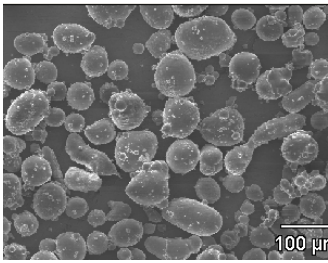
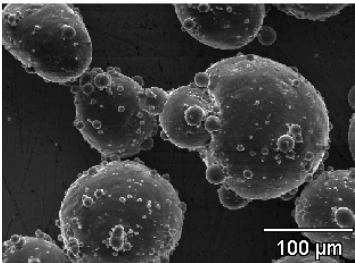
The microstructure was determined using a scanning electron microscope (SEM) “Merlin” (CarlZeiss, Germany). Preparation, processing and analysis of obtained data were carried out with the help of Smart SEM (CarlZeiss, Germany). Visualization of the surface morphology of the samples was carried out with a resolution of 1024×768 points with an accelerating voltage of 20 kV.

Tensile tests were carried out at room temperature using a Shimadzu AG-50kNXD testing facility under quasistatic loading. The tensile properties, such as yield strength ($\sigma_{0.2}$, MPa), ultimate tensile strength (σ_b , MPa), and strain to failure (δ , %) were measured.

Results and Discussions

Morphologies, chemical composition of the Al-12Si powder in their size distributions are presented in Table 1. Powder Al-12Si of the Russian brand “AKD12” is manufactured on the original installation “UR-9”.

Table 1. Chemical composition of alloy powder Al-12Si of brand “AKD12”.

Size of particle powder SEM-Images	$\leq 45\mu\text{m}$	45-80 μm	80-140 μm
			
Al, mas. %	85.6 \pm 0.5	82.2 \pm 0.2	82.5 \pm 0.5
Si, mas. %	12.7 \pm 0.5	14.8 \pm 0.5	12.0 \pm 0.3
Fe, mas. %	1.0 \pm 0.2	1.1 \pm 0.4	0.8 \pm 0.2

The fracture surfaces of SLM of processed Al-12Si at different laser scanning speeds are shown in figure 1. The porosity could be observed for the SLM processed sample. Dimples could be observed on the fracture surface, which indicates a typical ductile fracture. On the other hand, except the spherical pores, the interface of molten pool also appears on the fracture surface. Due to the high length/width ratio of interfaces of the molten pool, they cause the stress concentration region, which is an important reason for the reduction of tensile strength and ductility. A higher magnification image (Figure 1) shows that it is a mixture of fragile and ductile fracture. Additionally, the agglomerated silicon group appears also on the fracture surface. During the tensile loading, the Si rich region presents a low ductility and causes cracks [3].

The mechanical properties of the fabricated Al-12Si alloy are shown in Table 2. Al-12Si specimens are produced by selective laser melting (SLM) from gas atomized powders of the Russian brand “AKD12”, which are manufactured on the original installation “UR-9”. Room temperature tensile tests reveal the remarkable mechanical behavior of Al-12Si alloy specimens, which are produced by selective laser melting (SLM): the samples show yield and

tensile strengths of about 102 MPa and 425 MPa, respectively, along with fracture strain of 12%.

Table 2. Mechanical properties of SLM-products

Study	Yield strength $\sigma_{0.2}$, MPa	Ultimate tensile strength σ_B , MPa	Strain to failure δ , %
SLM-sample "AKD12"	101.6 \pm 3.0	425.1 \pm 24.7	12.1 \pm 2.2
SLM-sample Al-12Si [4]	260	380	3
SLM-sample Al-12Si [3]	225	350	6
SLM-sample Al-12Si [6]	274.8 \pm 8	296.1 \pm 20	2.2 \pm 0.3
Ingot Al-12Si [6]	104.2 \pm 11	192.3 \pm 15	9 \pm 0.5

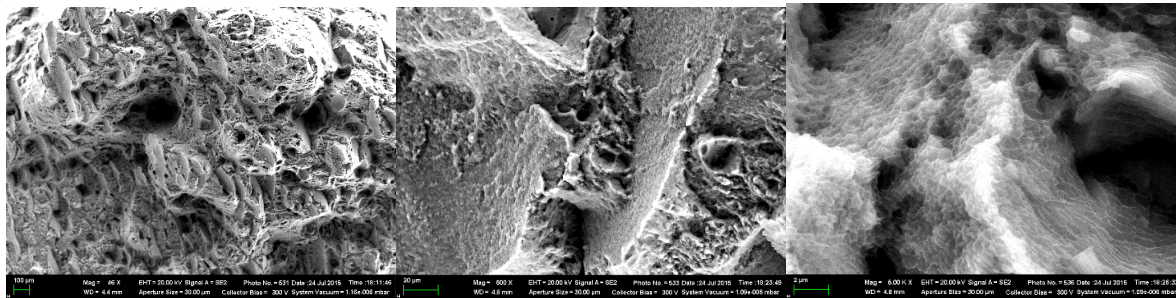


Figure 1. Microstructure of fracture surface of sample processed using laser scanning speed.

It is known that selective laser melting (SLM) demonstrates rapid cooling rates during processing. This enables the formation of an ultrafine eutectic microstructure in an Al-12Si alloy. Unlike the eutectic microstructure observed in Al-12Si alloys fabricated by conventional methods, the eutectic microstructure is characterized by spherical nano-sized Si particles embedded in the Al matrix. This ultrafine eutectic microstructure gives rise to significantly better tensile properties compared to traditionally fabricated Al-12Si parts. Upon solution treatment, the size of the eutectic Si particles, which are critical to the mechanical properties of Al-12Si parts, increases with increasing the solution treatment time. The bimodal distribution of the Si particle size is retained. However, the coarse and fine Si particles distribute homogenously in the Al matrix. Based on the detailed TEM study, it was found that spherical Si particles with a diameter below 100 nm formed at the Al grain boundaries as a result of the extremely high cooling rate during SLM. This micro-sized eutectic microstructure was believed to be the underlying reason for the very high tensile ductility of the Al-12Si alloy - 25% [5].

This study shows that Al-12Si alloy with exceptional tensile properties and ultrafine eutectic microstructure can be obtained by selective laser melting and subsequent solution treatment. The eutectic microstructure of Al-12Si alloys, especially the size of the Si particles, can be tailored effectively by varying the solution treatment time. This provides important insights into refinement of Al-Si alloys without the addition of other elements. Solution heat treatment of specimens was performed in air at 500 °C for up to 4 h, followed by water quenching [5].

It is known that the solidification microstructure of Al-Si alloys can be influenced by super heating with a finer and/or more uniform microstructure along with increased strength and ductility in samples that have undergone significant superheat prior to solidification [10–11]. The underlying reason has been attributed to the existence of two characteristic temperatures: the dissolution temperature T_d and the branching temperature T_b . Below T_d , the liquid contains aluminum and silicon-rich particles which have been inherited from the solid material. Once the T_d has been exceeded, these particles begin to

melt and above the branching temperature, T_b , molten alloy can be considered homogenous. Between T_d and T_b , Al-rich and Si-rich regions 10–200 nm in size co-exist within the molten pool [10]. This inhomogeneous microstructure will remain in the solidified alloys if the cooling rate is high enough ($\sim 10^3$ K/s). According to previous studies, T_d and T_b of Al-12Si alloys should be around 1080 ± 30 and 1290 ± 30 °C, respectively [10]. This temperature is much higher than the liquid's temperature of Al-12Si alloys (577 °C). Given that measuring the temperature in the melt pool in such short time is currently not possible, the temperature distribution upon heating within the melt pool in this study was estimated based on the transient heat transfer model using COMSOL™ [3]. The maximum temperature is at the centre of the molten pool and reaches about 1439 °C, which lies above T_b of Al-12Si alloy. However, it can be seen that the temperature of a large portion of the melt pool lies in between T_d and T_b of Al-12Si alloy. Hence, a large portion of the Al-12Si alloy melt pool probably undergoes a super heating in the temperature range between T_b and T_d . This will lead to an inhomogeneous microstructure of the molten pool of Al-12Si. The cooling rate is also estimated (based on the simulation) to be above $\sim 10^3$ °C/s for most parts of the melt pool. This super-high cooling rate will help to retain the abovementioned inhomogeneous microstructure. Therefore, it has been observed that Si particles around 10–100 nm in size and a supersaturated Al matrix are expected to form in the as-fabricated Al-12Si alloy. The growth of these nano-sized Si particles within the microstructure of the as-fabricated alloy was observed upon heat treatment.

Conclusions

In this work, the eutectic Al-12Si alloy was fabricated using selective laser melting (SLM) from Powder of Russian brand “AKD12”. Due to the high cooling rate of the SLM process, the Al-12Si alloy presents an ultrafine microstructure which consists of cellular Al-rich, α -Al and nano-sized Si particles. This ultrafine microstructure gives rise to tensile strength properties compared to the conventional casted Al-12Si alloy. During tensile tests at room temperature, remarkable mechanical behavior was revealed: the samples demonstrated yield and tensile strengths of about 102 MPa and 425 MPa, respectively, along with fracture strain of 12%. The study of the crack surface morphology was undertaken by the example of a sample. Except the spherical pores, the interface of molten pool also appears on the fracture surface, which indicates a mixture of fragile and ductile fracture. Additionally, the agglomerated silicon group also appears on the fracture surface.

References

- [1] Olakanmi E O, Cochrane R F and Dalgarno K W 2015 A review on selective laser sintering/melting (SLS/SLM) of aluminum alloy powders: Processing, microstructure, and properties. *Progress in Materials Science* **74** 401-477
- [2] Berman B 2012 3-D printing: The new industrial revolution. *Business Horizons* **55** 155-162
- [3] Li X P, Wanga X J, Saunders M, Suvorova A, Zhang L C, Liu Y J, Fang M H, Huang Z H and Sercombe T B 2015 Selective laser melting and solution heat treatment of refined Al-12Si alloy with a controllable ultrafine eutectic microstructure and 25% tensile ductility. *Acta Materialia* **95** 74-82
- [4] Prashanth K G, Scudino S, Klauss H J, Surreddi K B, Löber L, Wang Z, Chaubey A K, Kühn U and Eckert J 2014 Microstructure and mechanical properties of Al-12Si produced by selective laser melting: Effect of heat treatment. *Materials Science & Engineering A*. **590** 153-160
- [5] Kang N, Coddet P, Dembinski L, Liao H and Coddet C 2017 Microstructure and strength analysis of eutectic Al-Si alloy in-situ, manufactured using selective laser melting from elemental powder mixture *Journal of Alloys and Compounds* **691** 316-322
- [6] Suryawanshi J, Prashanth K G, Scudino S, Eckert J, Prakash Om and Ramamurty U 2016 Simultaneous enhancements of strength and toughness in an Al-12Si alloy synthesized using selective laser melting. *ActaMaterialia* **115** 285-294
- [7] Maskery I, Aboulkhair N T, Aremu A O, Tuck C J, Ashcroft I A, Wildman R D and Hague R J M 2016 A mechanical property evaluation of graded density of Al-Si10-Mg lattice structures, manufactured by selective laser melting. *Materials Science & Engineering A*. **670** 264-274

- [8] Samuel A M, Garza-Elizondo G H, Doty H W and Samuel F H 2015 Role of modification and melt thermal treatment processes on the microstructure and tensile properties of Al-Si alloys. *Materials & Design* **80** 99-108
- [9] Olakanmi E O 2013 Selective laser sintering/melting (SLS/SLM) of pure Al, Al-Mg, and Al-Si powders: Effect of processing conditions and powder properties. *Journal of Materials Processing Technology* **213**(8) 1387-1405
- [10] Calvo-Dahlborg M, Popel P S, Kramer M J, Besser M, Morris J R and Dahlborg U 2013 Superheat-dependent microstructure of molten Al-Si alloys of different compositions studied by small angle neutron scattering. *Journal of Alloys and Compounds* **550** 9-22
- [11] Chikova O A, Nikitin K V, Moskovskikh O P and Tsepelev V S 2016 Viscosity and electrical conductivity of liquid hypereutectic alloys Al-Si. *Acta Metallurgica Slovaca* **22** (3) 153-163